FINAL REPORT

FURTHER DEVELOPMENT AND TESTING OF THE METABOLIC GAS ANALYZER

NASA Contract No. NAS 9-12759

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Manned Spacecraft Center
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1.0 INTRODUCTION AND SUMMARY

This contract (NAS 9-12759) continued development of a novel metabolic monitor utilizing a mass spectrometer and digital computer to perform measurement and data reduction, resulting in print-out of breath-by-breath values for O_2 consumption, CO_2 production, minute volume and tidal volume. The most significant novelty lies in measurement of flow by the introduction of a continuous flow of tracer gas (krypton) to the expired gas stream, coupled with computation of flow as a reciprocal function of tracer concentration. The use of a common mass spectrometer to monitor all gases of interest--including the flow monitoring tracer--assumes time synchronization of all signals, permitting semi-instantaneous computation of all parameters of physiological interest.

The primary objectives of this contract were to: 1) Reduce the pressure drop of the "flow splitter", in which the tracer gas is added to a fraction of the expired gas; 2) Optimize the mixing of the tracer gas with the sample in the splitter to increase the range of linearity of the flow measurement; and 3) Determine and correct the cause of an apparent error in CO_2 measurement (+20%) noted in human tests at the conclusion of the previous contract. The design goals were to reduce the pressure drop to one inch of water at 600 liters/min flow, and to extend the range of linear flow measurement to 1000 liters/minute.

The results of these modifications are summarized in the following sections of this report.

A high level of engineering support was also provided to NASA for man-testing at MSC which confirmed that the major goals of the program had been achieved within the limitations superimposed by other equipment.

2.0 WORK PERFORMED

2.1 Refurbishment of GFE

The mass spectrometer (MS), computer, and interface electronics were received without visible damage in shipment. However, the equipment had been damaged extensively in previous shipments, resulting in "normal" poor connector contact, noisy potentiometers, etc. The MS internal sweep generator circuitry, in particular, had not operated properly during final tests on the previous contract.

When the mass spectrometer was started, it was found that the RF-generator tank coil form had melted, making the mass scan circuitry inoperative. One circuit board and the RF-chassis were rebuilt by Finnegan. It was then discovered that a power supply transformer had developed a shorted turn, requiring replacement. Finally, several integrated circuits in different power supplies were replaced before the MS could be operated. In particular, the power supply which regulates the ionization energy (electron beam accelerating voltage) had failed, providing a non-adjustable and poorly-regulated 69 volts dc. This failure may have been the cause of the CO_2 error noted in testing human subjects at the conclusion of the previous contract.

After making these repairs, it was possible to operate the MS under computer control, although the internal scan system remained very noisy. However, since this feature is a convenience, rather than a necessity, this circuit problem was not corrected.

Other indications that the equipment is no longer reliable were observed. These include failure of the filament supply to come on and failure of the printer to print until circuit boards are shifted in their connectors. Since this type of failure did not occur during routine operation, and extensive replacement of

parts would be required to correct the difficulty, no effort was made to correct these problems except on a day-to-day basis. While these conditions obviously reduced efficiency, it was apparent that the real objectives of this contract could not be accomplished within the available funding--unless the equipment was repaired and maintained on this minimal basis.

2.2 Design of Flow Splitter

The flow splitter used on the previous contracts had a pressure drop (ΔP) of about 4-1/2-inches of water at 600 liters/min flow. The design was modified to provide fewer parallel paths--each of larger diameter--to reduce the pressure drop to one inch of water at 600 liters/min on a theoretical basis. A better hole pattern was selected, improving the ratio of open-to-closed areas for the cell, but it was also necessary to increase the diameter of the hole pattern to obtain the required number of parallel paths. A new inlet tube was designed, therefore, to provide the necessary transition from mouth-piece diameter to the larger flow splitter diameter. The basic splitter concept is illustrated in Figure 2-1.

The design used stacked plastic plates with registered hole patterns to facilitate alteration of splitter length. Since three capillary probes are required, the minimum number of plates is three, and this may be increased by odd integer values. The optimum cell will be as short as possible (minimum ΔP) to accomplish satisfactory mixing (range of linearity).

Another deficiency of the previous design was corrected by providing means of more accurate positioning of the capillary probes used to introduce the tracer gases and to withdraw the MS sample. The probes were spring loaded against adjustment nuts with 40 threads per inch, providing a resolution of about two turns for full traverse of the probe across the mixing hole. In retrospect, finer resolution would have been very advantageous in linearizing the flow curve for the desired shorter splitter (5 plates), while the adjustment was satisfactory for the maximum length splitter (9 plates). In addition, it would have been very advantageous to have had reversible-but-positive position locking, other than by using Loc-Tite® on the adjustment nut threads.

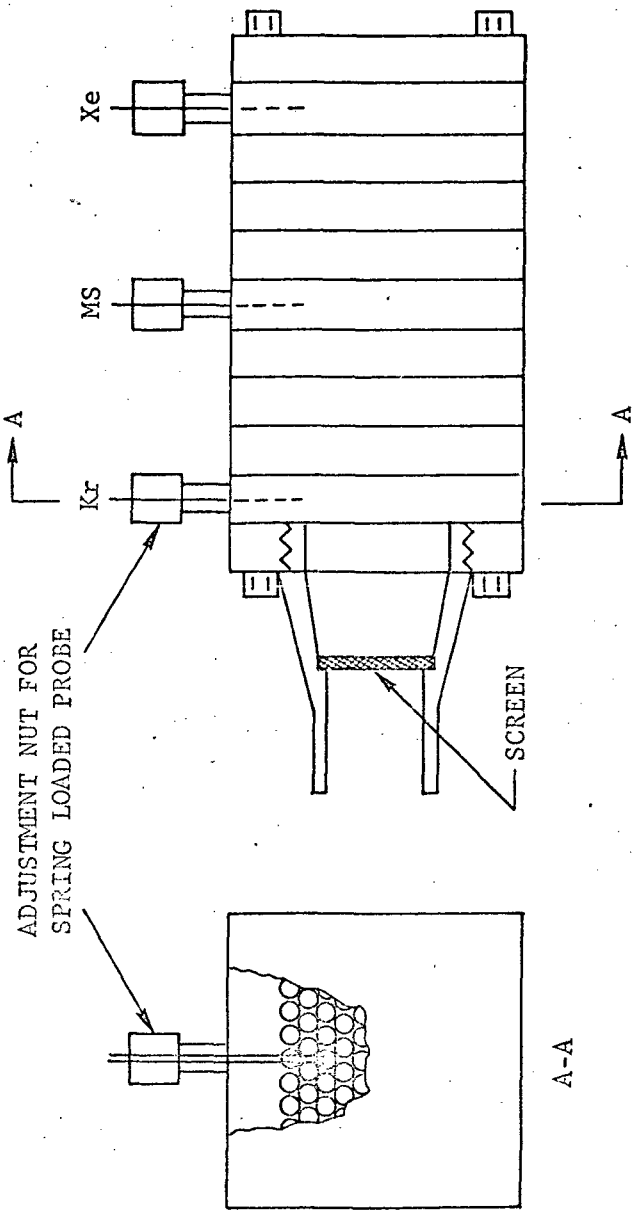

Figure 2-1. Improved Flow Cell

A GFE Technology, Inc. (TI) Linurmass flowmeter was sent out for verification of calibration prior to use in linearizing the flow splitter by probe positioning. Unfortunately, it failed during the process of investigating the effect of shortening the splitter. Before the TI flowmeter failed, it had been established that 9 plates provided ±5% linearity to 500 liters/min, and that 3 plates could not be made to work over the 0-300 liter/min range. Five plates were being tested when the reference flowmeter failed. A new TI flowmeter was borrowed from Instra-Tech, Inc., linearization of the 5 plate splitter to within ±5% for 0-500 liters/min was completed, and the probes were locked using Loc-Tite. When tested at NASA-MSC, the splitter showed errors in excess of ±10% in the 0-to-500 liter/min range. Several possible reasons for this apparent change are detailed below.

During installation of a protective cover around the probe capillaries prior to shipment to NASA-MSC, the krypton probe was stressed in a manner which broke a soft solder joint to a D-washer, allowing the probe to rotate. It was assumed that this caused the loss of calibration, and the krypton probe was unlocked and rebuilt. It was initially assumed that the MS probe had not moved, and it had previously been demonstrated that the other tracer probe position was not critical. However, attempts to linearize the splitter by repositioning the krypton probe proved to be futile, the major uncorrectable error being due to a sharp drop in output in the 70-to-150-liter/min range. The MS probe was then freed and trial-and-error adjustment of the two probes was attempted, but the large (10% or more) bend in the 70-to-150-liter/min range persisted.

All notes from the linearization efforts at Anaheim were reviewed, and it was discovered that no 5-plate curves obtained prior to substitution of the borrowed TI flowmeter showed acceptable linearity in the 70-to-150-liter/min range. It was then concluded that the borrowed TI flowmeter (brand new) may have had an accidental compensating non-linearity, resulting in the seemingly excellent linearity obtained in Anaheim. The splitter length was increased from 5 to 9 plates, and linearity within ±5% was easily obtained by adjustment of the Kr and MS probes. The positions of the adjustment nuts and capillaries were then locked with epoxy cement.

2.3 CO_2 Error

Considerable effort was directed toward determination of the CO_2 response linearity of the MS. It was demonstrated that the MS was linear from 0 to 9% CO_2 in mixtures of air, N_2, and air and N_2 plus 1% each of Kr and Xe. In retrospect, it appears that this elaborate testing may not have been necessary, and that the hardware failures described above may have been occurring during final testing under the previous contract, resulting in the 20% high data for CO_2 production. The most probable causes would be failure of the ionizing energy supply, and whatever sequence of failures ultimately resulted in destruction of the RF tank coil. In any event, following refurbishment of the MS, tests with many gas mixtures indicated that the CO_2 calibration was within about 1% for all combinations of composition.

2.3.1 Modifications of the Calibration Program

The original calibration program allowed maximum time for reading each mass per unit change to assure optimum accuracy. However, experience had indicated that the relative sensitivities to O_2, N_2 and CO_2 drifted with time of MS scan on the operational program, and that the DAC outputs for the calibration gas never agreed with the known composition on which the calibration was based. Accordingly, the calibration program was modified to provide for continuous, cyclic scans until the system could have time to stabilize before striking the teletype key to command use of the next complete scan for calibration calculations. Later testing indicated that several minutes of cycling did not greatly improve the performance. Possibly a completely new program, as nearly identical to the operational program as possible, would eliminate this difficulty. However, it is probable that the effect stems from the electron multiplier characteristics, and that it would not be observed with a different MS. Furthermore, these errors could not produce more than a few percent, and a relatively reproducible, error in final results because of the automatic drift correction features of the operational program. Consequently, further effort toward solution of this problem was not within the scope of the subject contract.

The calibration program was also modified to allow selection of m/e increments for the mass scan routine used in locating the mass peaks. Prior to this modification, a minor shift in location of Kr and/or Xe resulted in non-optimum scanning. Presently, a much larger drift may occur before manual patching of the start-stop scan numbers will be required for good calibration.

2.3.2 Special Program Patches for Using the MS for Gas Analysis

To use the DAC $\%O_2$, $\%N_2$, $\%CO_2$, etc., outputs to analyze the variety of calibration gases, it was necessary to modify the operational program to allow calculation to continue when both the Kr and Xe concentrations exceeded their thresholds (INCRH and INCRK in the program). It was also necessary to eliminate the automatic tracer zero offset updating to avoid random insertion of erroneous values. A program patch labelled "MAS as Analyzer" was provided to accomplish these objectives. With this patch, the thresholds are never exceeded, allowing the DACs to continue updating, and the tracer zero corrections are forced to zero. A second patch tape, which restores the normal operational program, was also provided.

Finally, a patch tape labelled "Adds Kr and Xe" was provided, with a companion to restore the normal conditions. This patch adds the P_{Kr} and P_{Xe} signals to the summation of pressures used to obtain the $\%N_2$, $\%O_2$ and $\%CO_2$ outputs. The operational program omits the partial pressures of Kr, Xe and H_2O in order to provide DAC outputs which are the percentages prior to dilution by the tracers, and on a dry basis. This patch is useful only when analyzing samples containing Kr and Xe, and its use avoids having to apply a correction factor for Kr and Xe to the other DAC outputs.

2.3.3 Poor Stability of MS CO_2 Sensitivity in Final Testing

While good results were obtained with numerous gas mixtures containing CO_2 in Anaheim, it should be noted that the MS appeared to be degrading rapidly during testing in January, 1973, at NASA-MSC. In particular, morning-to-afternoon calibration results indicated a shift of +12% for CO_2 and -3% for Kr relative to the sensitivity of N_2. While the source of this drift was not identified, it is possible that it is related to instability in one of three mass resolution adjustments.

3.0 RESULTS OF TESTING AT NASA-MSC

3.1 Static Flow Curve

The linearity of the final 9-plate flow splitter was determined against a Quantum Dynamics flow meter, the absolute calibration of which was not established. The results are shown in Figure 3-1, with a 10-fold expansion of both axis for 0-50 liters/min data. Later tests indicated that the linearity was still good to 300 liters/min, but that the calibration had changed by about 10% at 450 liters/min. It is possible that poor locking of one or both probes allowed a small shift in position. It is also possible that the stack of plates slide relative to each other because the design required a dowel-pin-type fit, for the four clamp bolts, and only poor fitting threaded stock was available when the length was changed from five to nine blocks.

3.2 Dynamic Flow Response

Pump tests indicated that the flow sensitivity was nearly 20% lower for pump tests than for static flow. Furthermore, considerable noise in the flow DAC output was observed for a large volume stroke (3 liters) at 30 strokes/min rate. The addition of a single screen to the flow splitter inlet tube greatly reduced the noise and slightly affected the disagreement with the static flow calibration. In retrospect, it appears probable that the tracer and MS probes should have been positioned deeper in the flow cell. The probes were located in the third hole in from the wall, which had been satisfactory for a uniform inlet diameter. In this case, however, this position is outside the minimum inlet diameter, and it is probable that the flow in the tubes at the probe location was less than average for dynamic variations. Under steady-state (static) conditions, the flow was probably more evenly divided among all tubes than it was on the average for a flow pulse.

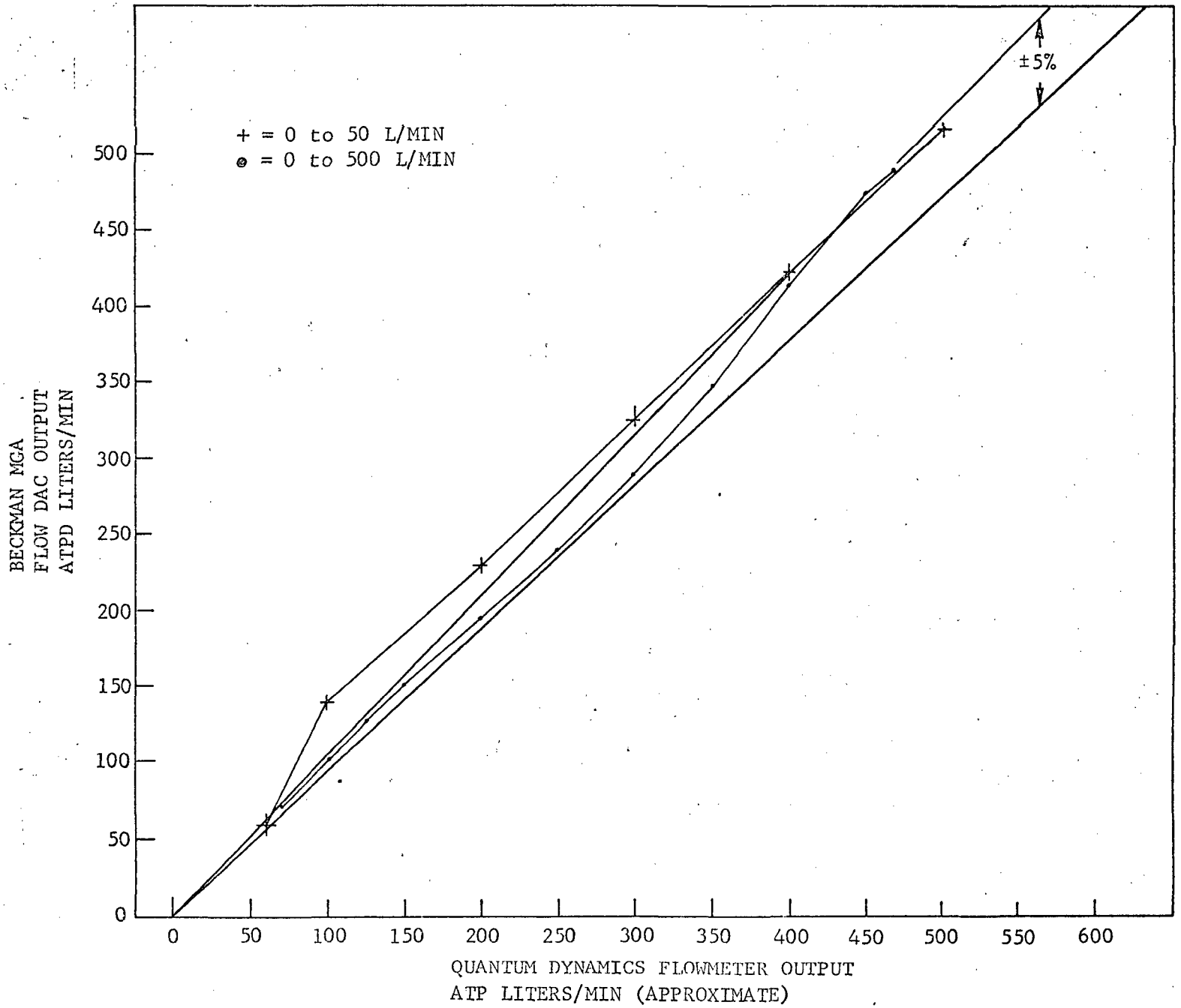

Figure 3-1. Static Flow Curve

3.3 Pressure Drop vs. Flow Rate

Tests at Anaheim indicated that the 9-plate flow splitter would have a pressure drop of one inch of water at 600 liters/min as predicted during design. Tests at NASA-MSC, however, indicated one inch of water at 450 liters/min, as shown in Figure 3-2. This test was made before the single screen was added. Based upon prior data, one screen should not add more than about 0.3 inch of water pressure drop at 450 liters/min.

3.4 Alteration of Constants for Final Man-Testing

Considerable effort was spent in determining final constants for man testing. The mass spectrometer stability degraded badly, resulting in confusion of the first test results. Desirable conditions before testing are also summarized here for the record:

a. Recalibrate several times, if necessary, to obtain proper DAC outputs for $\%N_2$, $\%O_2$ and $\%CO_2$ on a known mixture.

b. Verify that the tidal volume readout on the Harvard Pump is 2.92 to 2.98 liters for a stroke of 2.97 liters at a rate of 10 to 20 strokes per minute. (This is actually about 20% low since TV is supposed to be in BTPS units.)

c. Perform man test as soon as possible after verifying a and b, above, to minimize probability of drifts of CO_2 and Kr sensitivity.

The following program modifications are also required:

d. Manual program changes:

Address	Deposit (octal)	Function
0131	0013	Drives flow DAC to zero for >500 liters/min
4477	0600	Divide flow by 2 setting
4503	0010	INCRK } Stops computing for
4505	0010	INCRH } low flows

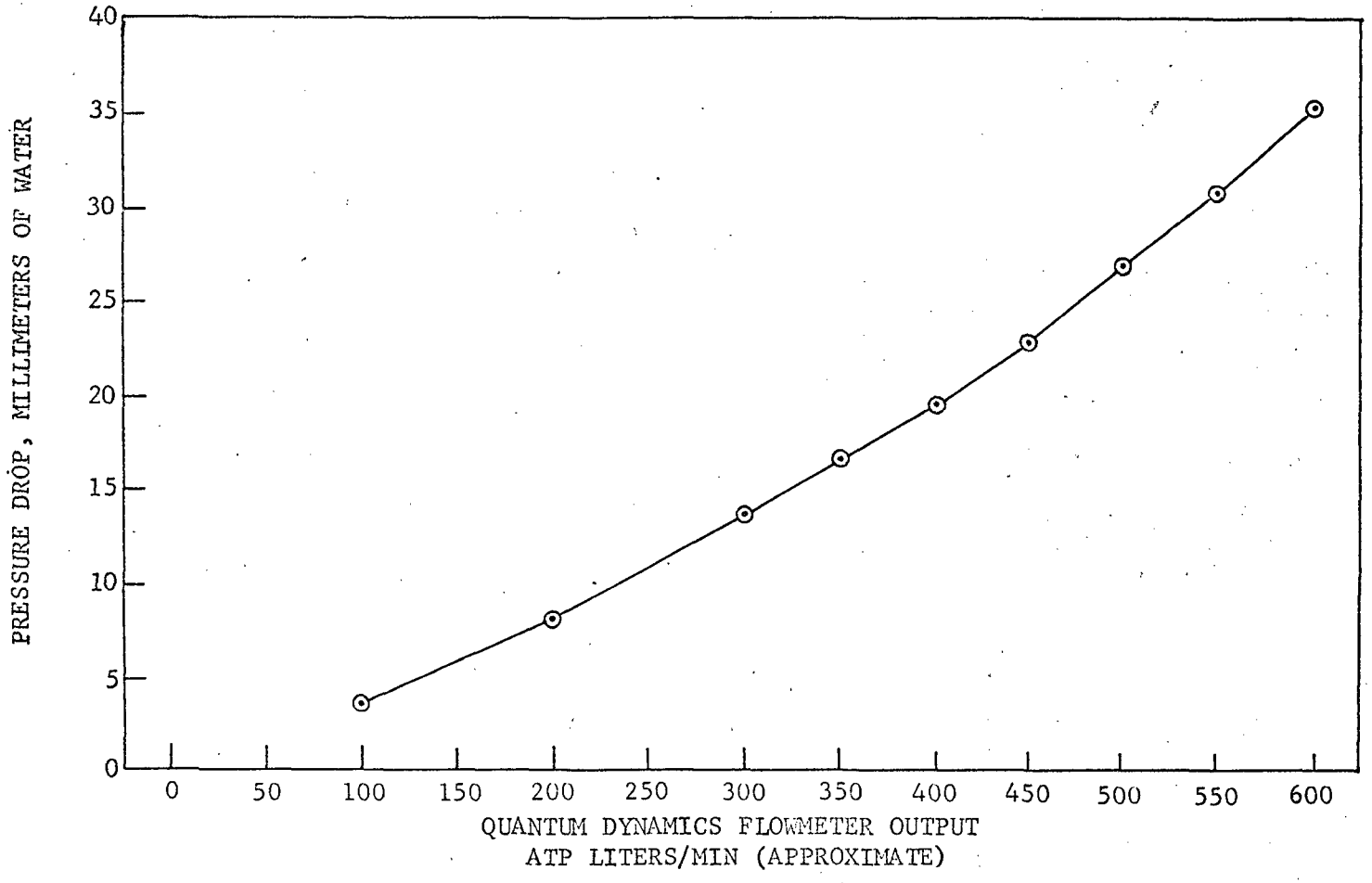

Figure 3-2. Pressure Drop Across Splitter

e. Use 5100 utility routine and teletype to enter as required.

1. Krypton Flow = C_K = Actual flow (STPD lit/min) x 619 tubes x 0.944
   = 0.3483 in final testing in January 1973

   If entered during calibration, it need not be re-entered. C_K is located at 4466.

2. VOLD = dead volume correction = 75 (corresponding to 50 ml of dead volume outward from the MS probe to free air).

   VOLD is located at 4507. The program enters 20, which assumes that the air outside the splitter is free of expired residual. The use of 50 ml reduces the $\Delta\dot{V}_{O_2}$ and $\Delta\dot{V}_{CO_2}$ results by about (1 - 50 ml/tidal volume), each breath.

4. The flow DAC upper limit should be computed as

   $$\frac{\text{Desired flow for 5 V DAC output}}{C_K \times 1.31} = 1094 \text{ for final test.}$$

   This limit affects the flow DAC output only, having no effect upon the printed final data. The limit thus computed is in ATPD units, and agrees with the final static curve (not the pump data).